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Approach to the potential production of giant reed in surplus saline lands of Spain

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Abstract

Growing energy crops on marginal land has been promoted as a way of ensuring that biomass production involves an acceptable and sustainable use of land. Saline and saline-prone agricultural lands represent an opportunity for growing energy crops avoiding the displacement of food production and contributing to restoration of degraded land. Giant reed (*Arundo donax* L.) is a perennial grass that has been proposed as a promising energy crop for lignocellulosic biomass production while its tolerance to salinity has been proved. In this work, the identification of surplus saline lands that could be irrigated with saline waters for growing tolerant-energy crops (giant reed) in the mainland of Spain and the assessment of the agronomically attainable yield in these limiting growing conditions were undertaken. To this purpose, a GIS analysis was conducted using geo-databases related to saline areas, agro-climatic conditions, irrigation water requirements, agricultural land availability, restrictions regarding the range of electrical conductivity tolerated by the crop, competition with agro-food crops and irrigation water provisions. According to the approach developed, the irrigated and saline agricultural area available and suitable for biomass production from giant reed amounted up to 34 412 ha. The agronomically attainable yield in these limiting conditions was estimated at 12.7 – 22.2 t dm ha^{-1} yr^{-1} and the potential production of lignocellulosic biomass, 597 338 t dm yr^{-1}. The methodology followed in this study can be applied to other target regions; it allows the identification of this type of marginal lands, where salinity-tolerant plant species could be grown for bioenergy purposes, avoiding competition with agro-food crops, and where soil restoration measurements should be undertaken.

Keywords: *Arundo donax*, geographic information systems, giant reed, lignocellulosic biomass, marginal land, salinity

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Introduction

Growing energy crops on marginal land has been promoted as a way of ensuring that biomass production involves an acceptable and sustainable use of land. The condition of 'marginal' may be ambiguous and site-specific; a piece of land may be marginal in a specific region or for a certain purpose, but it may be suitable for a different objective and even its quality can be considered no marginal in another location. Therefore, availability and suitability of marginal land for biomass production is surrounded by uncertainties among the wide-ranging estimates (Dale *et al.*, 2010; Lewis & Kelly, 2014). Actually, there are three separate definitions of marginal land: land unsuitable for food production ('because the land is not productive enough'); ambiguous low-quality land ('land not necessarily unsuitable for food production but where food production is less productive'); and economically marginal land ('land where cost-effective agricultural production is not possible under a given set of conditions') (Turley *et al.*, 2010; Shortall, 2013). Even though there is not a complete agreement on the definition of marginality, saline and saline-prone agricultural lands are certainly covered by the former concepts and they may represent an opportunity for growing energy crops avoiding the displacement of food production and contributing to restoration of degraded land.

The causes of soil salinization may be divided into natural and human-induced factors. Natural causes are subdivided into land (climate, geology, hydrology, etc.) and soil factors (texture, structure, compaction rate, etc.) (Tóth *et al.*, 2008). The latter factors are mainly based on land management and degradation. Thus, high salt contents (sodium, potassium, magnesium and calcium, chloride, sulphate, carbonate) in parent materials or groundwater lead to primary salinization (i.e. by natural processes) whereas human practices such as inappropriate irrigation or overexploitation of aquifers drive to secondary salinization (Tóth *et al.*, 2008).

Some ways for remediating saline soils and for taking advantage of them are proper agronomic practices, use of salt-tolerant crops and phytoremediation

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(Hasanuzzaman *et al*., 2014). Nevertheless, the response of plants to water and saline stress conditions may be the closure of stomata to reduce water losses, which would inhibit photosynthesis. This effect leads to reduction in plant growth and productivity. In addition, salt accumulation in soils reduces its hydraulic conductivity, which diminishes soil water availability (Cosentino *et al*., 2013). The development of biomass production from crops tolerant to limiting conditions – particularly drought and salinity – is among the main targets for crop management in Mediterranean areas (Araus *et al*., 2002; Cosentino *et al*., 2013).

Giant reed (*Arundo donax* L.) is a perennial grass that has been proposed as a promising energy crop for lignocellulosic biomass production in marginal, abandoned or set-aside agricultural land while its tolerance to salinity has been evidenced within the EU FP7 OPTIMA project (Curt *et al*., 2014; Sánchez *et al*., 2015). Actually, the tolerance of giant reed to salinity conditions and its physiological effects have been tested in several studies and regions, such as Italy, Spain, USA and Australia (Williams *et al*., 2009; Zema *et al*., 2012; Cosentino *et al*., 2013; Sánchez *et al*., 2015). In the study by Williams *et al.* (2009), it was found that some robust giant reed stands were able to tolerate electrical conductivities of soil extracts of 35–45 dS m^{-1}. Other studies (Calheiros *et al*., 2012) have showed the potential of giant reed for polishing organic matter and nitrogen from a high-salinity effluent from a tannery's wastewater (13.3–19.3 dS m^{-1}) in constructed wetlands. Moreover, giant reed has been recently cited in the European Union Directive 2015/1513 as 'non-food cellulosic material'; therefore, its cultivation for biofuels can be counted for the national targets of the EU Member States and its contribution is not subjected to the 7% limit of the final consumption of energy in transport in 2020.

Regarding the study of bioenergy potential production in degraded lands, different methodologies and assessments at different World regions and scales may be found in the bibliography (Milbrandt & Overend, 2009; Wicke *et al*., 2011; Zhuang *et al*., 2011; Nijsen *et al*., 2012; Tenerelli & Carver, 2012; Kang *et al*., 2013). Methodologies for identification of saline soils at regional scale are also quite abundant in the literature, mainly based on geographic information systems and remote sensing tools (Douaoui *et al*., 2006; Acosta *et al*., 2011; Bouaziz *et al*., 2011; Melendez-Pastor *et al*., 2012; Ochieng *et al*., 2013). On the other hand, the specific case of soil salinity assessment for biomass production from dedicated energy crops is less widespread: for example, a worldwide analysis of the extent and location of salt-affected soils and its potential to produce biomass from forestry plantations was conducted by Wicke *et al*., 2011. To the best of our knowledge, no assessment of surplus saline soils for biomass production has been conducted at a national scale in Spain so far. By surplus saline lands, it is meant those areas classified simultaneously as saline and saline-prone lands that would not represent competition with the agro-food production if giant reed were grown.

The specific objectives of this work were the following: (i) to develop a method to identify and assess the saline or saline-prone marginal lands that could be irrigated with saline waters for growing tolerant-energy crops such as giant reed, and (ii) to apply this method to the case study of Spain in order to estimate the lignocellulosic biomass potential production of giant reed.

Materials and methods

Identification of saline and saline-prone areas

Saline agricultural lands (saline soils) and saline-prone lands (agricultural land irrigated with brackish or saline waters) were assessed altogether in order to estimate the area of land subjected to saline degradation processes that might be suitable for growing giant reed.

Regarding saline soils, the database of saline and sodic soils in the European Union (Tóth *et al*., 2008) was compiled and polygons referred to mainland Spain were extracted (Fig. 1). This database displays the calculated percentage share of salt-affected areas of the polygons within the Soil Mapping Units from the European Soil Database (European Commission and the European Soil Bureau Network, 2004). The three classes of soil salinity (more than 50% of the area with saline soils, less than 50% and potentially salt-affected areas) were selected as potential saline lands.

The identification of saline-prone land was based on the measurements taken by the control networks of water quality established by each of the 15 River Basin Districts (RBD) in Spain (Fig. 2) for the accomplishment of the Water Framework Directive for water protection and management (Directive 2000/60/CE).

The above-mentioned networks are divided in two sections, superficial and groundwater water control networks. In both cases, they evaluate different parameters of water quality, including water electrical conductivity (ECw) measured at 25 °C. Results of these measurements from some RBD control networks are available on their respective websites, but some databases need to be officially requested. Thus, data of ECw, measured at 25 °C, were gathered and compiled for the time period 2010–2013 from each RBD for both surface and groundwater control networks. The annual mean values for 2010 were calculated, geo-referenced and depicted in a geographic information system (GIS) environment (ArcGIS – Environmental System Research Institute – ESRI™). Average values of 2010 were taken for this work as the 2010 data set was the largest and most complete one from the compiled database for the analysed time period. These values are shown in Fig. 3.

Geostatistical analyses were conducted in order to interpolate ECw point data to continuous data in raster layers using the

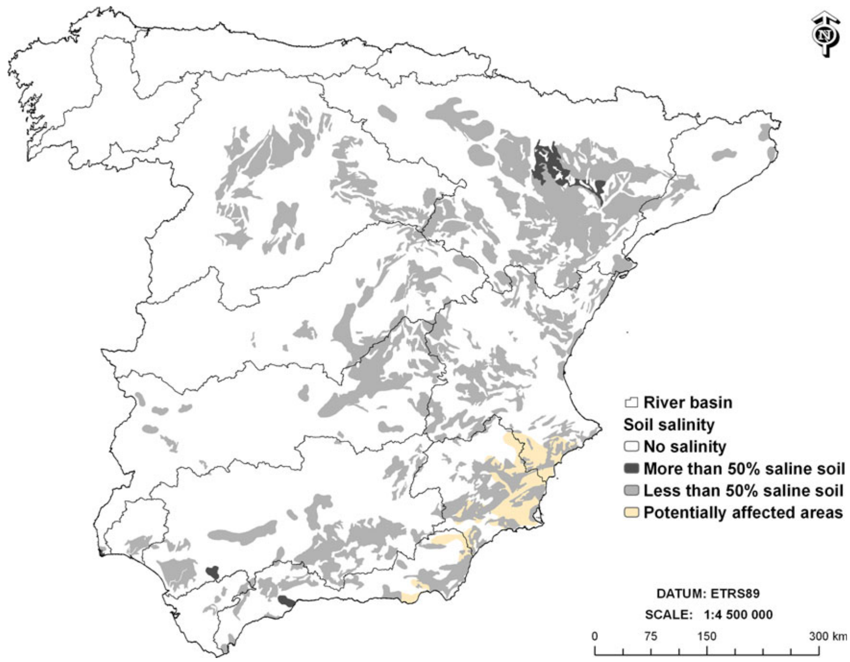

Fig. 1 Map of saline soils in mainland Spain. Geo-referenced information extracted from the European Soil Database (Tóth *et al.*, 2008)

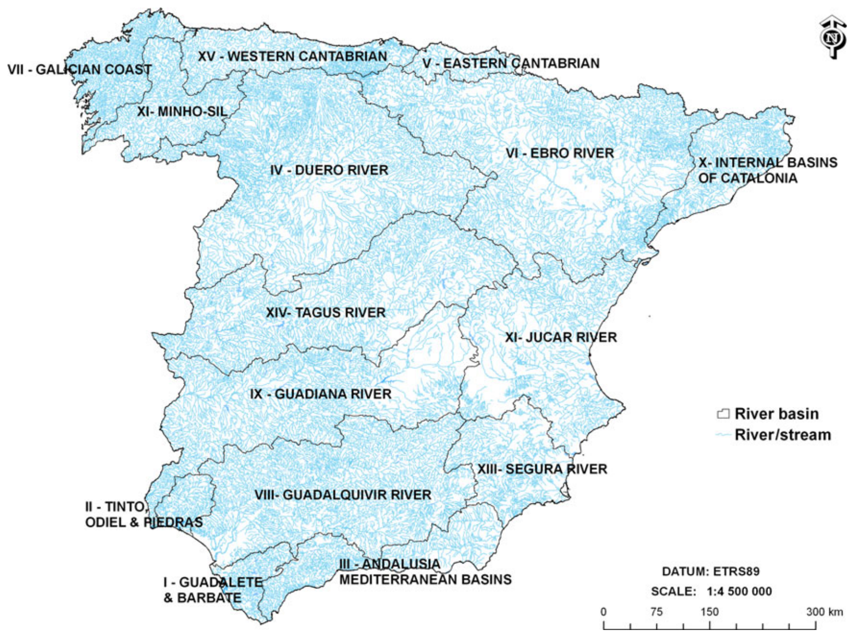

Fig. 2 River Basin Districts in mainland Spain.

Geostatistical wizard (ESRI™). Databases for surface and groundwater control networks were interpolated separately but also jointly with the integrated ECw database. ECw data from 3618 and 2242 points were collected from the groundwater and surface control networks, respectively. In both cases, 1% of the total point data were randomly selected and laid away as a subset for the subsequent model validation. The interpolation methods tested were deterministic (Inverse Distance Weighted, Spline, Local Polynomial and Radial Basis Function) and geostatistical (Krigging). Mean relative errors (MRE) and root-mean-squared errors (RMSE) of each interpolation method were calculated.

Once an ECw continuous data set was obtained, the average value in each area of irrigated land was calculated by means of the ‘zonal statistic’ tool, with the aim to assign values for ECw

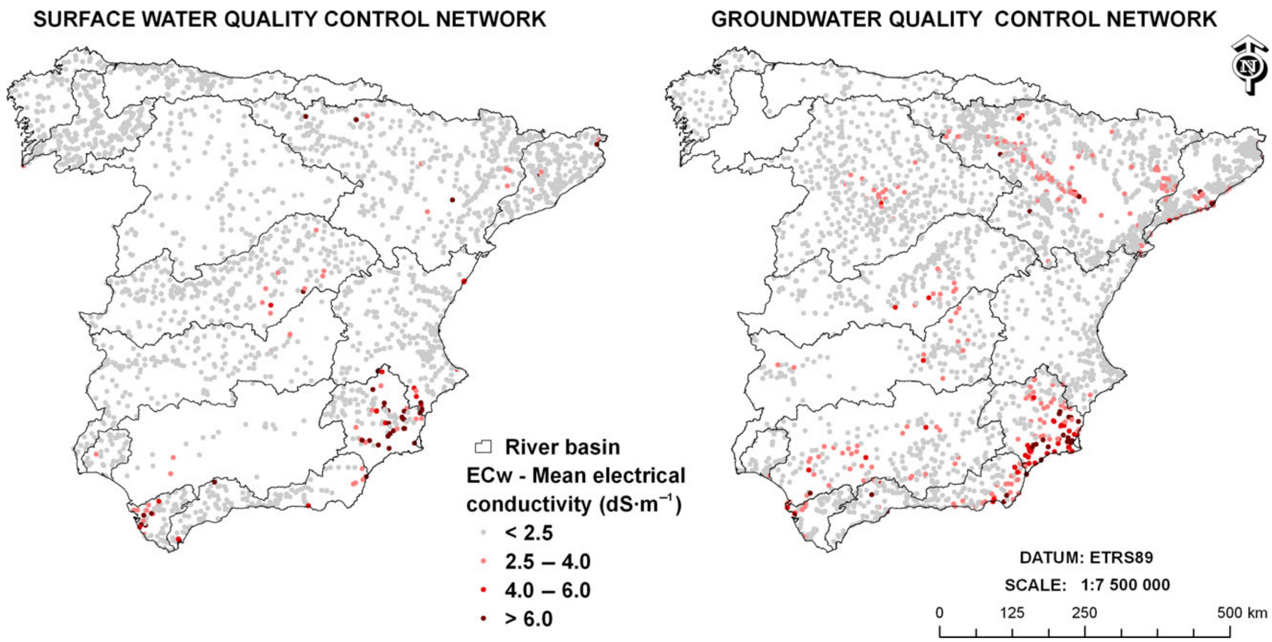

Fig. 3 Mean electrical conductivity of water (ECw) according to the control networks of water quality.

to each polygon. For this purpose, the class 'permanently irrigated agricultural land' from the Corine Land Cover 2006 vector data (http://www.eea.europa.eu/data-and-maps/data/clc-2006-vector-data-version-3) was used (henceforth, CLC2006). A correlation between the irrigation water origin: surface irrigation, groundwater irrigation and undifferentiated irrigation (a combination of the two types) and water quality control network was assumed. Thus, according to the information gathered from the Agricultural Demand Units (ADU) – see section Analysis of resource availability – one type of water origin was assigned to each irrigated land polygon and therefore its corresponding ECw.

Then, the electrical conductivity of saturated soil extract (ECe) was calculated from ECw in each polygon of irrigated land, by means of the equation by Ayers & Westcot (1985).

$$\mathrm{ECe} = \mathrm{ECw} \times 1.5 \tag{1}$$

According to consulted bibliography, several clones of giant reed are tolerant to salinity and are able to grow with ECe values up to 8–9 dS m^{-1} (Cosentino *et al.*, 2013), whereas irrigated cereals – wheat, barley, triticale – can tolerate 6 dS m^{-1} at the most (Rhoades *et al.*, 1992).

Therefore, the saline agricultural land available for growing giant reed was estimated by the selection of those polygons with an estimated ECe between 6 and 9 dS m^{-1} which centroids (geometric centres) were within the polygons of saline soils mapped by Tóth *et al.* (2008).

Estimation of crop requirements

Giant reed is known to be a perennial species adapted to limiting growing conditions, but it also needs some basic resources to be able to thrive and produce enough biomass. The methodology developed for this section aimed at the analysis and estimation of the crop requirements, in terms of crop cycle length and irrigation needs of giant reed in mainland Spain, to identify the irrigated land suitable for its cultivation.

The estimation of the crop cycle length was based on the calculation of the growing degree days (GDD, °C day), commonly used for measuring crop phenology and development with the concept of heat units (McMaster & Wilhelm, 1997) needed for plant growth. The irrigation needs were estimated from the crop coefficient (Kc), defined as the ratio of evapotranspiration (ETc) from a specific crop or soil surface to a reference ET value (Allen *et al.*, 2005).

The input data for the estimation of the crop cycle length and Kc of giant reed in Spain were extracted from experiments conducted in the Mediterranean region. Kc and water-use efficiency of giant reed for different growth stages were estimated from data of a field experiment conducted in Pisa in 2010 and 2011 (Triana *et al.*, 2014). The growth stages were identified as: initial (from crop sprouting to the beginning of stem elongation), crop development (stem elongation), mid-season (from the end of stem elongation to the beginning of canopy senescence) and late season (from canopy senescence to the end of water uptake). In our work, GDDs for each stage were calculated from data of Pisa-S.Giusto weather station (www.tutiempo.net/clima) assuming 10 °C as base temperature (Di Nasso *et al.*, 2011). Average data of both years were calculated and extrapolated to Spanish conditions (Table 1).

Following this approach, the length of giant reed growth cycle in Spain was spatially determined either by GGD or stage duration (days). For GGD calculation, the mean temperature for each set of 10 days was interpolated from mean monthly temperatures raster data set (National Meteorological Agency

Table 1 Growth stages and crop coefficient (Kc) (± standard deviation) of giant reed reported by Triana *et al.* (2014) and Growing Degree Days (GDD) calculated from climate data for this work

Year	Growth stage	Starting date	Kc	Stage duration (days)	GDD (°C day)
2010	Initial	29-Mar	0.67 ± 0.07	44	154
	Crop development	12-May	0.91 ± 0.14	25	182
	Mid-season	06-Jun	1.93 ± 0.09	103	1320
	Late season	17-Sep	1.38 ± 0.13	34	244
	Total	21-Oct	–	206	1900
2011	Initial	20-Mar	0.41 ± 0.06	43	262
	Crop development	21-May	1.11 ± 0.14	22	239
	Mid-season	12-Jun	1.55 ± 0.14	86	1158
	Late season	06-Sep	0.98 ± 0.12	45	427
	Total	21-Oct	–	196	2086
Average	Initial	24-Mar	0.54 ± 0.18	44	208
	Crop development	17-May	1.01 ± 0.14	24	211
	Mid- season	09-Jun	1.74 ± 0.27	95	1239
	Late season	12-Sep	1.18 ± 0.28	40	336
	Total	21-Oct	–	201	1993

of Spain – AEMET, 2010a) using Gommes' interpolation method (2) (Gommes, 1983):

$$\begin{aligned} T_{10-1} &= (5 \times T_{M-1} + 26 \times T_{M-2} - 4 \times T_{M-3})/27 \\ T_{10-2} &= (-T_{M-1} + 29 \times T_{M-2} - T_{M-3})/27 \\ T_{10-3} &= (-4 \times T_{M-1} + 26 \times T_{M-2} + 5 \times T_{M-3})/27 \end{aligned} \quad (2)$$

where $T_{10\text{-}1}$, $T_{10\text{-}2}$ and $T_{10\text{-}3}$ are the temperatures in each set of 10 days within a month and $T_{M\text{-}1}$, $T_{M\text{-}2}$ and $T_{M\text{-}3}$ are the mean monthly temperatures in the corresponding 3-month interval.

The starting date of the crop cycle was considered to be dependent on the mean minimum temperature (National Meteorological Agency of Spain – AEMET, 2010b), and the limit was set at 3 °C following the criterion by Emberger (1955) when frost period is less frequent. Subsequently, GDD and the Kc for each set of 10 days were geo-spatially estimated.

Irrigation needs for agriculture depend on both crop requirements and climatic characteristics of the studied area. Hence, the monthly effective precipitation – Pef – (fraction of rainfall that is really available for plants) was estimated following Brouwer and Heibloem method (3) (Dastane, 1978) from monthly accumulated data (P) provided in a raster data set (National Meteorological Agency of Spain – AEMET, 2010c):

$$\begin{aligned} \mathrm{Pef} &= 0.8 \times P - 25 \quad \text{if} : P > 75\,\mathrm{mm\,month}^{-1} \\ \mathrm{Pef} &= 0.6 \times P - 10 \quad \text{if } P < 75\,\mathrm{mm\,month}^{-1} \end{aligned} \quad (3)$$

In addition, monthly evapotranspiration (PET) was also compiled from the data sets available at the Consortium for Spatial Information (CGIAR-CSI, http://www.cgiar-csi.org/) which are based on a globally modelled evapotranspiration (Trabucco *et al*., 2008) from a spatialized implementation of the Hargreaves (Hargreaves, 1994) evapotranspiration equation (Zomer *et al*., 2008). Only the monthly PET values for the giant reed crop cycle were gathered.

Gommes' interpolation method for accumulating variables was then used for calculating Pef and PET values for each set of 10 days from monthly values (Gommes, 1983):

$$\begin{aligned} \mathrm{PET}_{10-1} &= (5 \times \mathrm{PET}_{M-1} + 26 \times \mathrm{PET}_{M-2} - 4 \times \mathrm{PET}_{M-3})/81 \\ \mathrm{PET}_{10-2} &= (-\mathrm{PET}_{M-1} + 29 \times \mathrm{PET}_{M-2} - \mathrm{PET}_{M-3})/81 \\ \mathrm{PET}_{10-3} &= (-4 \times \mathrm{PET}_{M-1} + 26 \times \mathrm{PET}_{M-2} + 5 \times \mathrm{PET}_{M-3})/81 \end{aligned} \quad (4)$$

where $\mathrm{PET}_{10\text{-}1}$, $\mathrm{PET}_{10\text{-}2}$ and $\mathrm{PET}_{10\text{-}3}$ represent the evapotranspiration values in each set of 10 days within a month and $\mathrm{PET}_{M\text{-}1}$, $\mathrm{PET}_{M\text{-}2}$ and $\mathrm{PET}_{M\text{-}3}$ are the mean monthly evapotranspiration in the corresponding 3-month interval.

Then, the irrigation needs of giant reed per set of 10 days were calculated according to the expressions (5) and (6).

$$\mathrm{ETc} = \mathrm{ETo} \times \mathrm{Kc} \quad (5)$$

$$\Delta r = \mathrm{ETc} - \mathrm{Pef} \quad (6)$$

where ETc is the crop evapotranspiration and Δr represents crop irrigation requirements for an optimal yield.

Water irrigation requirements for each set of 10 days were then calculated using ESRI Spatial Analyst tool. Finally, the zonal statistics tool was used for the calculation of the mean values of irrigation requirements in each polygon of irrigated agricultural land during the whole crop cycle.

Analysis of resource availability

This section aims at the compilation of geo-referenced data regarding the basic agrarian resources for the cultivation of giant reed in Spain: land and water.

The irrigated agricultural land was based in the Corine Land Cover 2006 vector data. The class 'permanently irrigated agricultural land' was considered as the agricultural land potentially available for crops with accessible irrigation systems.

As regard to availability of water for crop irrigation, each RBD in Spain is in charge of elaborating its respective Hydrological Plan (2010–2015) (HP) for water management, in accordance with the Water Framework Directive of the European Union. Within each Plan, water demand is estimated for

human consumption, agricultural (crops + livestock) uses, industrial uses and 'others uses'. According to the water demand for the different uses and the water availability in the river basin, each RBD designates the amount of water for each of the above-mentioned uses, which includes the water provision for crops irrigation.

The information provided by the Hydrological Plans in Spain is rather heterogeneous: some Plans specifically allocate the water provision for each of the existing crops in the river basin (considering the water requirements of each crop); others specify the water provision per type of irrigation system; certain Plans differentiate between surface and groundwater provision; water provisions refer either gross and net amount depending on the analysed Plan; the geo-referenced unit varies and the water provision is allocated per Agrarian County (an ensemble of municipalities) or per Agricultural Demand Unit – ADU (irrigation area with similar characteristics in terms of location, water origin or irrigation community to which the area belongs). Hence, a homogenization process was conducted in this work to build a geo-referenced database of general water provision for crop irrigation at national scale. Assumptions made for this purpose were the following:

- When the HP made the distinction between irrigation systems, sprinkling-type irrigation was chosen.
- Linked to the type of irrigation system, 75% efficiency was assumed (Confederación Hidrográfica del Duero, 2012) for sprinkling-type irrigation in case the water provision was given in gross figures.
- When no differentiation between the origins of the irrigation water (surface or groundwater), undifferentiated irrigation was assigned and consequently, the ECw corresponding to the integrated database as well – see section Identification of saline and saline-prone areas.

This way the water provision for crops irrigation in each Hydrological Plan in Spain was gathered, homogenized and introduced in the GIS environment (Fig. 4).

As the geo-referenced units – to which water provisions were allocated – slightly differed from the polygons of irrigated agricultural land from CLC2006 data set, an assignation process between the two layers was conducted. To this purpose, water provision for the three types of water origin (surface, groundwater and undifferentiated) was converted into continuous raster data sets with a pixel size of 100 m. The zonal statistics tool was used to calculate the mean water provision for each polygon of irrigated land in CLC2006 as well as the number of pixels from each type of water origin within each polygon. In those with more than one water origin type, the predominant one was assigned.

Estimation of biomass potential production

Once the crop requirements were assessed in terms of crop cycle length and irrigation water and the availability of the related agricultural resources was evaluated, the potential production of biomass (stems and leaves) under limiting conditions was estimated. The methodology consisted in the application of yield constraints on the crop potential yield, similarly to the bases of the Global Agro-Ecological Zones methodology from FAO (Fischer *et al*., 2012), in order to estimate the agro-climatic attainable yield.

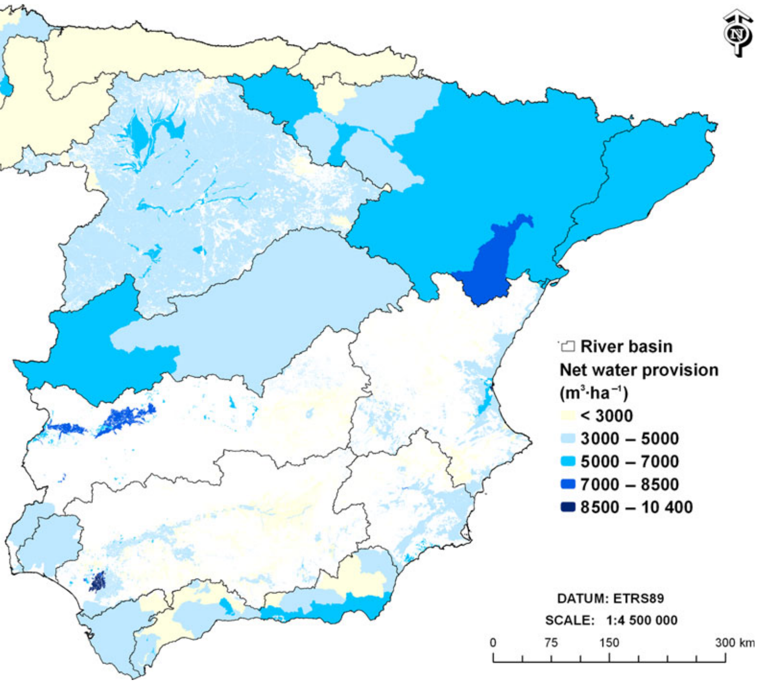

Fig. 4 Net water provision for crops irrigation (m^3 ha^{-1}) in mainland Spain according to the homogenization process conducted from data in Hydrological Plans of Spain.

Thus, the yield constraints considered in our work were as follows: water deficit (from water requirements and irrigation water provision previously assessed) and soil salinity (in accordance with the estimated ECe and the salinity tolerance of giant reed).

Regarding soil salinity, data of ECe and giant reed yields were gathered from the literature (Williams & Biswas, 2009 [In Singh, 2013]; Zema *et al.*, 2012; Cosentino *et al.*, 2013); afterwards, the respective decline in yield was calculated (Table 2).

The yield constraint related to water deficit was assessed from an experiment conducted during four consecutive years in Sicily (Cosentino *et al.*, 2014). Yield losses at the three different levels of water deficit tested – in terms of maximum evapotranspiration restitution – were compiled (Table 3). The irrigation amount was inferred from the water-use efficiency and rainfall values.

Hence, a function of yield loss was built for each parameter from literature data using 28.9 t dm ha^{-1} (Cosentino *et al.*, 2014) as a reference value for giant reed potential yield, including stems and leaves. In this way, the agro-climatic attainable yield was estimated for the limiting conditions of the identified saline areas.

Nevertheless, the above-mentioned reference value considered as the optimal yield may still be rather optimistic for regular conditions of water availability and soil quality in Mediterranean areas. Therefore, a sensitivity analysis was also conducted by reducing this reference value by 20% and 50% (23.1 and 14.4 t dm ha^{-1}, respectively), to which the yield loss functions were then applied. Thus, the lignocellulosic biomass potential production from giant reed in standard conditions under water and salinity stress was also estimated.

Results

Identification of saline and saline-prone areas

Of the 2 198 264 ha of the permanently irrigated agricultural land in Spain mapped by CLC2006, the area that was located within the saline soils area identified by Tóth *et al.* (2008) amounted to 644 581 ha. The irrigated agricultural land located in saline soils, broken down by origin of the irrigation water, was 25 680 ha for groundwater, 141 474 ha for surface water and 477 427 for undifferentiated origin-type water, according to the information compiled from the Hydrological Plans.

Table 2 Yield losses of giant reed vs. electrical conductivity (ECe) calculated from mean values reported by the respective authors. Significance of the relationship between ECe and yield loss: $P < 0.001$

Source	ECe (dS m^{-1})	Yield loss (%)
Cosentino *et al.* (2013)	2.2	0.0
	6.3	15.7
	9.1	44.5
Zema *et al.* (2012)	0.38	0.0
	0.6	2.4
Williams & Biswas	8.3	25.0
(2009) [In Singh, 2013]	12	50.0
	25	100.0

Table 3 Data of yield losses of giant reed vs. water deficit, calculated from mean values reported by Cosentino *et al.*, 2014. Significance of the relationship between water deficit and yield loss: $P < 0.001$

Year of experiment	Water deficit (%)	Yield loss (%)
1998/1999	0	0.0
	50	13.7
	70	29.8
1999/2000	0	0.0
	50	12.2
	74	34.6
2000/2001	0	0
	50	21.9
	76	40

Regarding the interpolation of ECw point data, the Inverse Distance Weighting (IDW) interpolation method was the one that best performed among the methods tested for both groundwater and surface water control networks, according to the root-mean-square error (RMSE). The validation of the interpolation from the integrated database (with the groundwater and surface networks combined) showed a RMSE of 8.744 dS m^{-1} and a mean relative error of 30%. IDW data interpolation showed that ECw ranged from 0.192 to 15.502 dS m^{-1}. According to that, ECe values varied from 0.288 to 23.253 dS m^{-1}.

As it can be seen in Fig. 5, soil salinity in most irrigated agricultural lands of mainland Spain could be classified as low (ECe < 4 dS m^{-1}) or moderately low (4 < ECe < 6 dS m^{-1}). The Segura river basin (XIII in Fig. 5) showed the highest proportion of land with estimated values of ECe over 6 dS m^{-1}. River basins V (Eastern Cantabria) and VII (Galician coast) did not include irrigated land according to CLC2006.

Thus, according to the analysis conducted in this work there are 65 588-ha saline-prone agricultural lands in mainland Spain with 6 < ECe < 9 dS m^{-1}, of which 34 412 ha are located on the saline soils identified by Tóth *et al.* (2008). This latter saline land area is mainly concentrated in the Segura River Basin (Fig. 6) and was taken in our study as the saline agricultural land area suitable for growing giant reed without food market distortion.

Estimation of crop requirements and the resource availability

The annual growth cycle of giant reed in the Spanish conditions was found to extend from early March to late

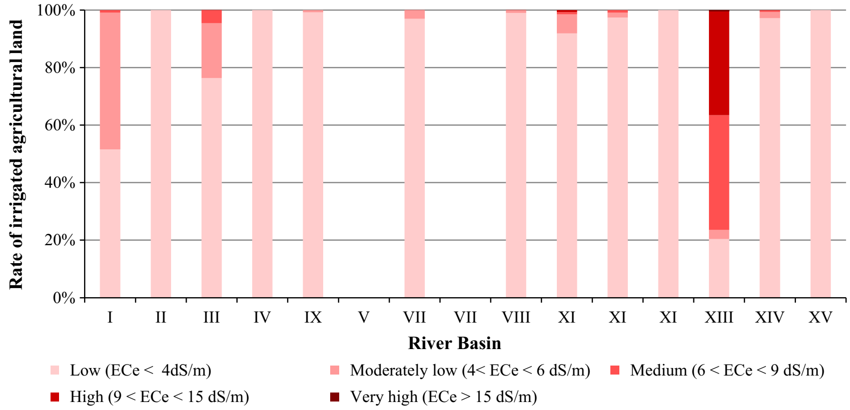

Fig. 5 Distribution of salinity classes of the irrigated agricultural land within each River Basin according to the electrical conductivity of the soil extract (ECe). Key to River Basins as in Fig. 2.

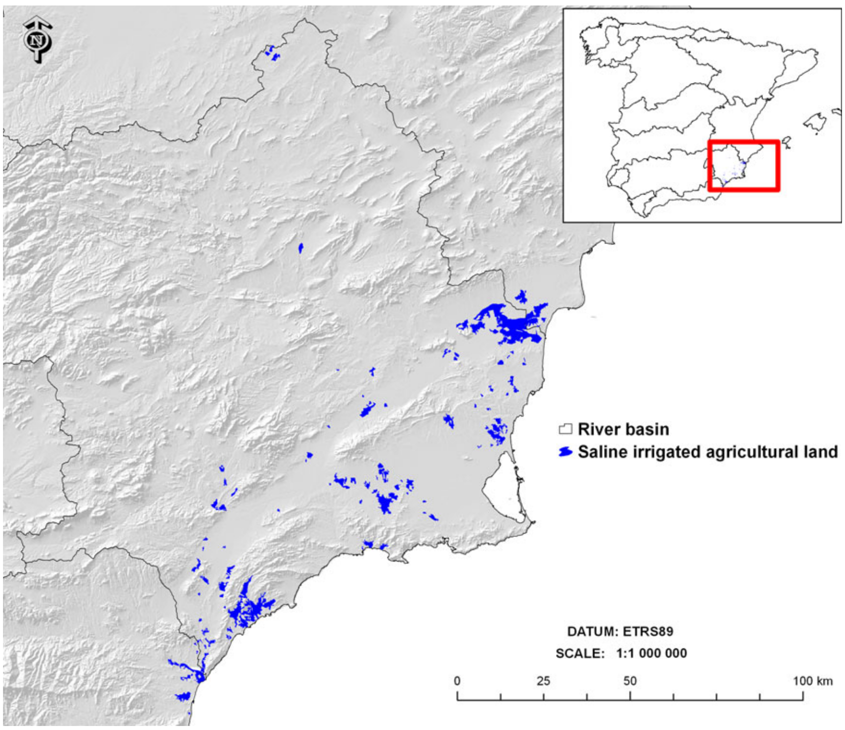

Fig. 6 Saline-irrigated agricultural land suitable for growing giant reed.

November, depending on the region. Kc for the growth cycle was estimated per set of 10 days, but for better interpretation, it is displayed in Fig. 7 per fortnight.

The irrigation water requirements for optimal yield of giant reed in Spain were estimated at the range 2500–11 700 $m^3\ ha^{-1}\ yr^{-1}$ taking into account the values of Kc, PET and Pef during the annual growth cycle (Fig. 8). Specifically, in the saline-irrigated agricultural lands identified as suitable for growing giant reed ($6 < ECw < 9$ dS m^{-1}) the irrigation requirements varied between 7918 and 10 710 $m^3\ ha^{-1}\ yr^{-1}$.

Water provision for crop irrigation established by the Hydrological Plans in the potential giant reed growing area varied from 1226 to 5585 $m^3\ ha^{-1}\ yr^{-1}$, according to our approach.

Biomass potential production

As the identified saline area has limiting conditions for plant growth (salinity and water deficit), the effect of yield constraints was estimated from yield reduction functions built for giant reed.

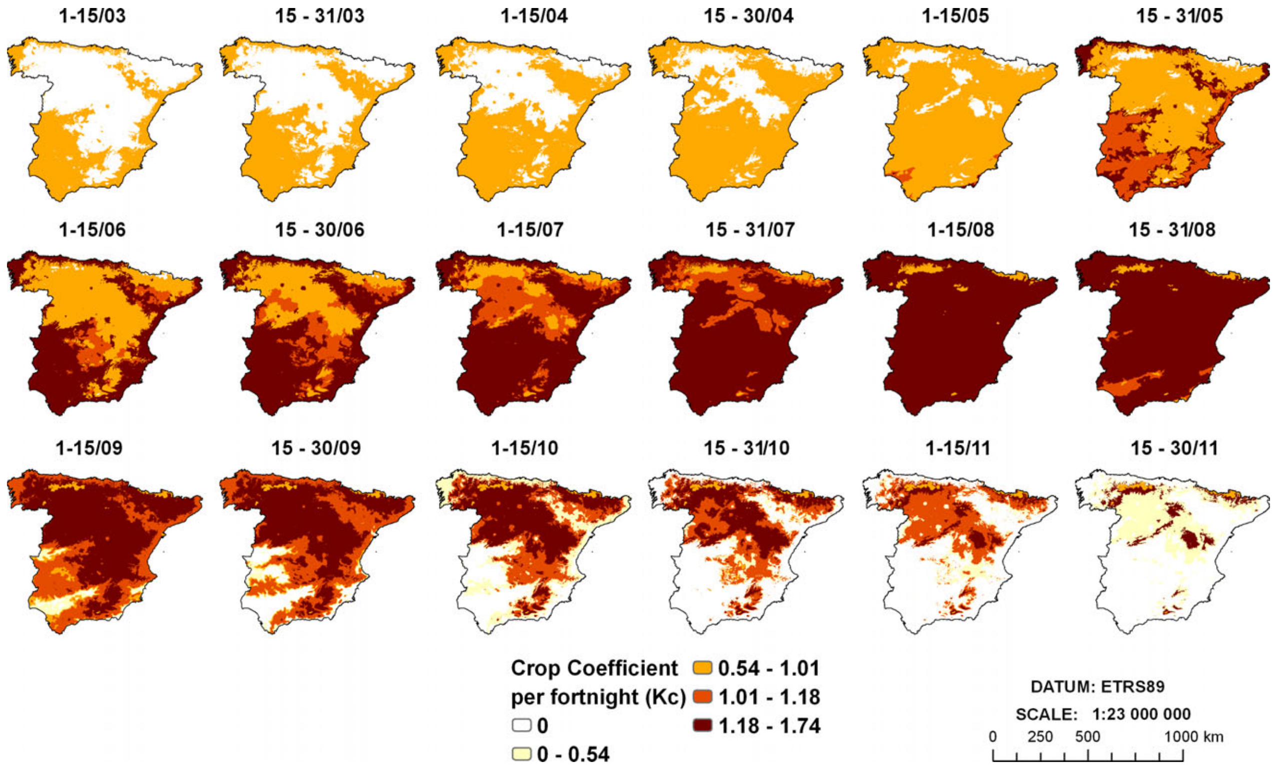

Fig. 7 Map of the evolution of the crop coefficient (Kc) of giant reed during its growth cycle in mainland Spain as estimated per fortnight (starting day–ending day/month).

For soil salinity constraint, the best fit (R^2 = 0.970) from compiled data (Table 2) was found for a linear function as shown in Fig. 9. It was expressed as (7):

$$Y_{\mathrm{Lsal}}(\%) = 0.042 \times \mathrm{ECe}\ (\mathrm{dS\ m^{-1}}) - 0.0386 \tag{7}$$

where Y_{Lsal} is the yield loss (%) in relation to the potential crop yield due to salinity conditions and ECe is the electrical conductivity of the soil extract in dS m^{-1}.

Regarding the water-deficit constraint, a polynomial equation (R^2 = 0.966) was obtained (Fig. 10) from data shown in Table 3. The equation is given in (8):

$$Y_{\mathrm{Lwat}}(\%) = 0.71 \times \mathrm{WD}^2(\%) - 0.0437 \times \mathrm{WD}(\%) + 0.0012 \tag{8}$$

where Y_{Lwat} is the yield loss (%) due to water deficit and WD is the water deficit measured in percentage of the estimated irrigation water requirement.

The yield reduction of giant reed in the identified saline area ranged from 21.5% to 33.2% and from 1% to 28%, for the salinity and water-deficit limiting conditions, respectively. Therefore, the agronomically attainable yield considering these limiting growing conditions resulted in the range 12.7–22.2 t dm ha^{-1} yr^{-1} (Fig. 11). Hence, the potential production of lignocellulosic biomass from giant reed under the limiting growth conditions of the identified saline areas was estimated at 597 338 t dm yr^{-1}.

The sensitivity analysis resulted from the reduction of the assumed optimal yield in 20% and 50% (23.1 and 14.4 t dm ha^{-1}, respectively) showed agronomically attainable yields with minimum values between 10.2 t dm ha^{-1} (20% reduction) and 6.4 t dm ha^{-1} (50% reduction) and maximum values of 17.8 and 13.1 t dm ha^{-1}, respectively. The consequently biomass potential production would decrease to 477 770 t dm yr^{-1} and 298 564 t dm yr^{-1}, respectively.

Discussion

Marginal lands have been defined by Soldatos (2015) as lands not worth cultivating with agro-food crops because of a number of bio-physical or economic constraints such as low soil quality, water and salinity stress, extreme climate conditions, soil and terrain handicaps, long distance to the market or state intervention, among others. Hence, saline lands and saline-water irrigated lands in which traditional food crops would not be feasible may be considered as marginal land, where no competition or displacement of food production would be caused. To this end, this study addressed the

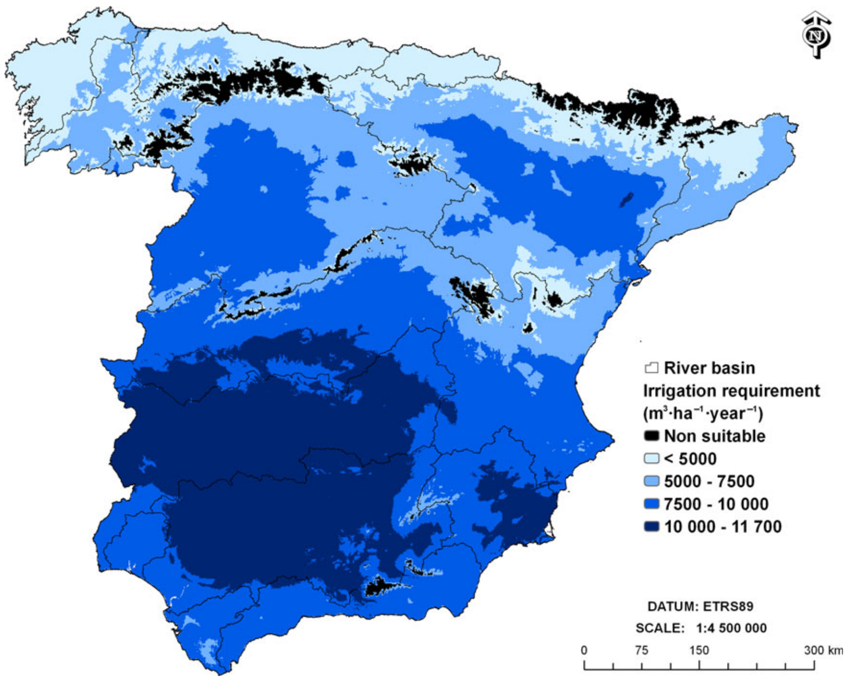

Fig. 8 Continuous data (raster) of irrigation water requirements for optimal giant reed yield in mainland Spain. Nonsuitable areas are referred to regions where the growth cycle would not be completed.

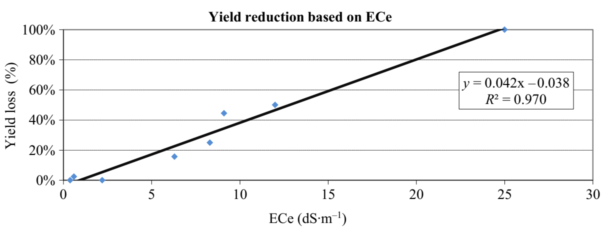

Fig. 9 Yield reduction function (%) based on the electrical conductivity of the soil extract (dS m^{-1}).

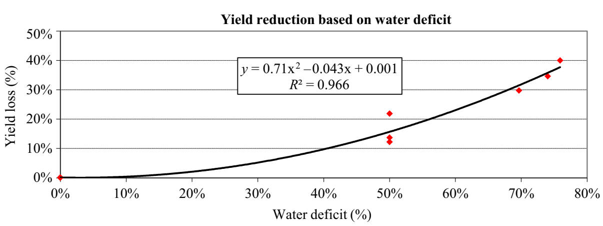

Fig. 10 Yield reduction function (%) based on water deficit (%) according to irrigation water requirement of giant reed.

identification of that type of lands and the estimation of the potential production of lignocellulosic biomass from giant reed, a saline-tolerant species.

The identification of marginal land to be devoted to the production of lignocellulosic biomass from giant reed pursues a number of positive effects in terms of soil restoration and phytoremediation: unlike annual crops, perennials provide larger quantities of residual organic matter that improve the buffer capacity of the soil against rapid changes in salinity (Darwish *et al.*, 2005; Acosta *et al.*, 2011). Additionally, salinization of most soils in the south-east of Spain has been often induced by the use of poor-quality irrigation water. The introduction of drip irrigation systems would counteract this effect (Acosta *et al.*, 2011). Drip irrigation can be used for growing giant reed instead of sprinkler or flood irrigation, systems that are often used for growing field crops in dry environments. Furthermore, cultivation of salt-tolerant and high water-use-efficiency crops would contribute to decrease the risk of soil salinization. Soil erosion and polluted runoff are also reduced by the substitution of conventional crops grown on marginal lands for bioenergy with low-input perennial grasses (Campbell *et al.*, 2008). Consequently, the work here presented could help policy makers to know the potential size of the bioenergy resources while avoiding the abandonment of agricultural land and its progressive degradation.

Tóth *et al.* (2008) updated the map of salt-affected soils of Europe from two databases: i) the European Soil Database at 1 : 1 000 000 scale (ESDB), which characterizes distinct soil types grouped in soils associations, and ii) the map of salt-affected soils in Europe (Szabolcs, 1974) which was an extension of the FAO/UNESCO Soil map of the World specifying salt limitations for

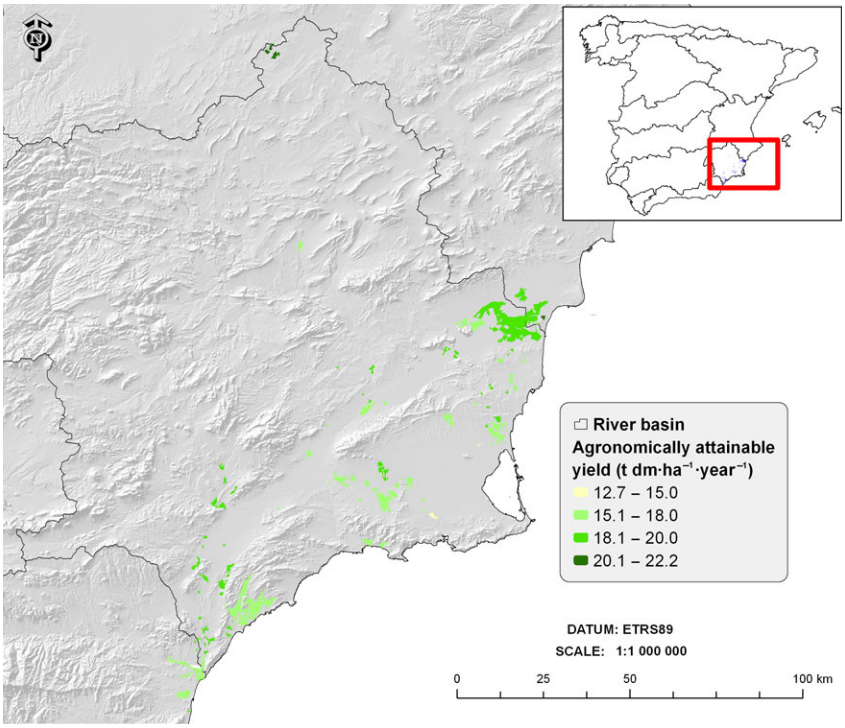

Fig. 11 Agronomically attainable yield (t dm ha^{-1} yr^{-1}) of giant reed in the identified saline agricultural areas.

agricultural activities. As it was not technically feasible to spatially delineate every characterized soil or soil association – Soil Typological Units (STU), they were grouped into Soil Map Units (SMU) which could be digitized, managed and depicted by a GIS. Therefore, the methodology used for mapping saline soils only allowed classifying SMUs according to the share of area covered by saline soils (more or <50% – see Fig. 1). Based on the valuable work by Tóth *et al.* (2008), the procedure followed in our study for downscale saline lands was focused on the estimation and identification of the saline or brackish water. Besides, this approach also allowed the identification of areas with saline-prone soils.

Soil salinity could evolve over time either positively or negatively, as a function of natural processes (primary salinization) and human interventions (secondary salinization). Taking into account the date of the publication considered in this work as a reference for saline soils identification (the year 2008), the use of complement databases to update soil base information would be adequate. To this end, the automatic and manual networks of ECw measurements, that compile data in the rivers and water bodies of Spain yearly, were used. In any case, further saline soil information would be needed to improve the current analyses.

Mapping soil salinity encounters difficulties due to large spatial and temporal variability of the saline condition. Many studies – aiming at the elaboration of saline soils maps – are based on survey instruments such as electromagnetic induction metres (Lesch *et al.*, 2005), which makes the mapping of large areas time-consuming and expensive. To lower survey costs, field spectroscopy and remote sensing have been widely used, but satellite imagery also presents limitations derived from spectral and spatial resolution (Fernández-Buces *et al.*, 2006). Thus, studies using remote sensing for this purpose have been applied to limited study areas (Kauter *et al.*, 2003; Fernández-Buces *et al.*, 2006; Madyaka, 2008; Melendez-Pastor *et al.*, 2012). On the contrary, our approach addresses a first approximation of mapping soil salinity areas at a national scale; besides the method here developed could be applied to other regions or study areas where similar geo-spatial information were available.

In the study by Melendez-Pastor *et al.* (2012), different digital image processing techniques were applied on multispectral images in order to analyse soil salinization processes in a coastal zone of south-east Spain, which is mainly devoted to irrigated farming. The study area was found to present soil electrical conductivities (ECe) from 1.38 to 4.71 dS m^{-1}. Even though the former work is not comparable to the present study in terms of working scale and techniques, the ECe values estimated in our work for the same area ranged between 3.1 and 6.9 dS m^{-1}. Another study (Herrero & Pérez-Coveta,

2005) analysed the trends on salinization in the Flumen irrigation district of Aragon (Northeast Spain) by direct measurements of soil salinity from three surveys (1975, 1985/1986 and 1999). The median ECe surveyed in 1999 for the considered saline soils was 1.94 dS m^{-1}, a similar value to the ECe values estimated in our study for that study area, which ranged between 1.3 and 1.9 dS m^{-1}. Therefore it can be inferred an acceptable correlation between the results of the above-mentioned studies and our values of estimated ECe. Nevertheless, the saline land areas identified in the current paper should be validated by measuring the ECe of soil samples in further studies.

Regarding the potential area for giant reed in Spain – identified according to crop requirements – the results obtained in our work are consistent with the distribution map of possible energy crops (including giant reed) in Europe reported Zegada-Lizarazu *et al.* (2010). Both studies show that the distribution area of giant reed covers most mainland of Spain, except for the highlands of NE and NW Spain where the period of time that would be suitable for growing giant reed is shorter than the duration of the growth cycle of this crop.

The Kc values estimated in this study are slightly higher than those adopted by Cosentino *et al.* (2014), who assumed the values they used for *Miscanthus x giganteus* (Cosentino *et al.*, 2007) to calculate the daily ETc and the irrigation needs. The irrigation crop requirements found in our work for Spain (2500–11 700 m^3 ha^{-1} yr^{-1}) were in line with the values reported for this crop in other studies, that is from 7360 to 12 350 m^3 ha^{-1} in the Mediterranean conditions of Italy (Borin *et al.*, 2013); 10 230 m^3 ha^{-1} under optimum water supply conditions in southern Italy (Zegada-Lizarazu *et al.*, 2010) and 7000 m^3 ha^{-1} for semi-arid conditions in Greece (Dalianis *et al.*, 1995).

In our work, the potential saline area for growing giant reed was restricted to the ECe range of 6–9 dS m^{-1} (4–6 dS m^{-1} ECw) in order to conduct a conservative assessment. As stated in other studies, giant reed may tolerate higher values of electrical conductivity like 12 dS m^{-1} ECe (Williams & Biswas, 2009) or 16 dS m^{-1} ECw (Sánchez *et al.*, 2015). If such values were assumed for our study, the potential area for growing giant reed in saline lands of Spain would be up to 84 885 ha and 87 782 ha, respectively. In any case, irrigation water with salinity of ECw > 2.4 dS m^{-1} is highly saline and considered not suitable for irrigation under ordinary conditions for traditional field crops (e.g. cereals and citrus) (Williams & Biswas, 2010). Thus, there would not be a considerable displacement of food production by the devotion of the identified saline area to giant reed cultivation.

In this regard, research has been recently conducted with the aim of identifying giant reed clones tolerant to water and salinity stress. In the study by Sánchez *et al.* (2015), the clones 'Martinensis' and 'Piccoplant' performed best in both limiting conditions. According to that study, giant reed seems to be more tolerant to salinity than to water deficit. Nevertheless, further development of highly salinity- and drought-tolerant clones of giant reed would be recommendable.

Limiting growing conditions that combine the factors: water deficit and saline conditions were assessed as the sum of both yield reduction factors for this study. In the study by Sánchez *et al.* (2015), the yield reduction observed in the treatment that combined water stress (25% field capacity) and saline conditions (16 dS m^{-1} ECw) was 66.3%, which represents a lower figure than for the sum of the separated limiting factors – 61.5% for water stress and 45.8% for salinity. In our work, the area identified with the harshest conditions – in terms of water availability and soil salinity – combined 64% water deficit and 7.9 dS m^{-1} ECe, which led to 26.4% and 29.5% yield reduction, respectively. From that, the agronomically attainable yield was estimated at 12.7 t dm ha^{-1} yr^{-1} for those conditions, which represented 55.9% combined yield reduction, leading to a more conservative assessment than the results obtained by Sánchez *et al.* (2015). Studies on the separate effect of water stress and saline conditions on biomass yield can be found in the literature (Williams & Biswas, 2010; Cosentino *et al.*, 2013, 2014). Nonetheless, to the best of our knowledge, there is no further research on the combining effect of both limiting factors when acting together, apart from the study by Sánchez *et al.* (2015). It is worth noting that the effect of stress factors on biomass yield in that experiment was studied for a period of only 2 months, not achieving the completion of the growth cycle of giant reed. In addition, the experiment was conducted with pot-grown plants. Hence, the effect of concurrent conditions of salinity and drought on giant reed yield needs further investigation.

Taking the factor of soil salinity separately, Sánchez *et al.* (2015) found statistical differences between the ECw treatment of 16 dS m^{-1} and the control treatment for total plant dry weight but not between 4 dS m^{-1} and the control. According to the yield reduction function estimated in our work, those conditions of salinity would lead to 96.6% and 21.3% yield reduction, respectively.

The methodology developed for the estimation of actual yields in the present study, based on yield limiting factors, was somewhat similar to the analysis conducted by Wicke *et al.* (2011). Their assessment of the technical and economic potential of forestry plantations on salt-affected soils, at a global scale, was based on

limiting factors applied on constraint-free yield of tree species, while saline soils were determined from the Harmonized World Soil Database (HWSD) (FAO *et al.*, 2008). Several factors hamper the comparison between both studies, namely the spatial resolution and scale of the analysis, irrigation assumptions, the energy crops considered and the land-use databases used, among others. Thus, the actual yields estimated by Wicke *et al.* (2011) ranged between 0 and 27 t dm ha^{-1} yr^{-1} with 3.1 t dm ha^{-1} yr^{-1} mean yield, whereas in our estimations the agronomically attainable yield of giant reed resulted in the range 12.7–22.2 t dm ha^{-1} yr^{-1} (17.4 t dm ha^{-1} yr^{-1} weighed mean). Besides, Wicke *et al.* (2011) considered the whole range of values for soil salinity (i.e. ECe > 16.0 dS m^{-1} but associated to low crop suitability and low yield) in their analysis. In contrast, we removed from our analysis the agricultural land with ECe > 9 dS m^{-1}, even though giant reed would be able to survive in such conditions yielding very low amount of biomass.

The potential biomass production from giant reed in the saline lands identified in this work resulted in 597 338 t dm yr^{-1}, an amount equivalent to 10.5·10^{6} GJ yr^{-1} primary energy, assuming 17.58 MJ kg^{-1} low heating value (LHV) of (https://www.ecn.nl/phyllis2/). Taking into account the yields assessed in the sensitivity analysis of the reference value (23.1 and 14.4 t dm ha^{-1}), the potential primary energy production would result in 8.4·10^{6} and 5.2·10^{6} GJ yr^{-1}, respectively. In this regard, it should be mentioned that the calorific value of giant reed biomass obtained from marginal soils might be different from the biomass produced in standard conditions. Several studies have been conducted focusing on the effect of water and salinity stress on yields, morpho-biometric and physiological parameters of energy crops (Sidella *et al.*, 2015; Zanetti *et al.*, 2015). However, to the best of our knowledge, the response of plants to salinity and drought in terms of the biomass energy value has not been deeply analysed. In any case, other factors regarding biomass harvesting and logistics (moisture content and biomass fractionation, among others) might have more relevant effects on the biomass energy content than the marginality of the production area. In fact, experiments of giant reed grown in water-deficit conditions in Madrid (Spain) carried out by the authors (publication pending) showed no statistical differences between water regimes for LHV. The weighed LHV mean was found 17.57 ± 0.42 MJ kg^{-1} (2.4% variation coefficient), taking into account the biomass partitioning into stems (82.4 ± 7.8%) and leaves (17.6 ± 7.8%). This value is almost the same as the LVH assumed in our work. However, further research on this issue would be needed.

The methodology developed in our approach can be applied to other study areas provided that geo-referenced data are available. Both methodology and results of the case study of Spain addressed the use of saline or saline-prone agricultural areas for biofuels avoiding competition with agro-food land uses while a crop cited as 'non-food cellulosic material' in the European Union Directive 2015/1513 is promoted.

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